Nanostructure

- Materials Growth
- Characterization
- Fabrication

More see Waser, chapter 2
Materials growth - deposition

Physical Vapor Deposition (PVD)

Chemical Vapor Deposition (CVD)

Gas → Solid

Deposition

Substrate

Kinetic process at surface

Complete pyrolysis on surface

Partial pyrolysis in boundary layer
Physical Vapor Deposition
• vacuum evaporation
• sputtering
• molecular beam epitaxy (MBE)

Chemical Vapor Deposition
• atmospheric pressure chemical vapor deposition (APCVD)
• low pressure chemical vapor deposition (LPCVD)
• plasma assisted (enhanced) chemical vapor deposition (PACVD, PECVD)
• photochemical vapor deposition (PCVD)
• laser chemical vapor deposition (LCVD)
• metal-organic chemical vapor deposition (MOCVD)
• chemical beam epitaxy (CBE)
Molecular Beam Epitaxy (MBE)
MBE chamber
RHEED monitoring the film quality
vacuum evaporation

Thermal evaporation

E-beam evaporation
Sputtering

Sample at cathode

Target at Anode and bombarded by high energy ions generated by a plasma discharge
Sputtering vs. evaporation

- Higher energy with sputtering produces higher packing densities and better adhesion if stresses are low.

- Greater variety of materials including alloys and mixtures can be sputtered than evaporated.

- Depositions can be made on temperature-sensitive substrates such as polymers.

- Deposition rates are lower for sputtering than for e-beam, but stresses can be higher.

- Sputtering provides better step coverage, while evaporation is more directional.

- Sputter equipment is more expensive.

- Sputtering optical multi-layers is more difficult.

- Sputtering involves a greater number of process variables than evaporation, but many of them are stable and repeatable, permitting sputtering to be automated.
Chemical Vapor Deposition (CVD)

a chemical reaction takes place between the source gases (precursors)
Chemical Vapor Deposition (CVD)

Gas measurement and metering
Transport of molecules by gas flow and diffusion
Transport of heat by convection, conduction, and radiation
Chemical reactions in the gas phase and at the surfaces
Plasma formation and behavior
Characterization of the resulting films
CVD vs. PVD

pros

• Excellent Step coverage
• Uniform distribution over large areas
• No compositional gradients across substrate
• No need to break vacuum for source changes
• More selective area deposition because of higher activation energy for reaction with foreign substances.

cons

• Mostly involve safety and contamination
• Hydrides and carbonyls are poisonous (especially arsine)
• Metalorganics are pyrophoric (ignite in contact with air)
• High cost for compounds with sufficient purity
Other thin film “growth” techniques

electroplating

Spin coating

BEFORE SPINNING  AFTER SPINNING
Materials Characterization Techniques

- Scanning Tunneling Microscope (STM)
- Transmission Electron Microscope (TEM)
- Scanning Electron Microscope (SEM)
- Atomic Force Microscope (AFM)
  and Scanning Probe Microscope (SPM) in general
Measures the tunneling current. Topographic information abstained from the feedback signal in constant current mode.

\[ \frac{dI}{dV} \propto \Gamma D_{\text{sample}}(E)D_{\text{tip}}(E + eV) \]

\[ \Gamma \propto e^{-2kd} \]
Scanning Tunneling Microscope (STM)
Manipulate individual atoms
Atomic Force Microscope (AFM)
Non-contact mode:
Van der Waals, electrostatic, magnetic or capillary forces

Contact mode:
Ionic repulsion forces

Dynamic contact (taping mode): Amplitude decreases at fixed frequency
Feedback loop keeps the amplitude constant. Signal from the feedback loop reflects force information, which depends on the materials, etc, and can be converted to height information.
Atomic Force Microscope (AFM)

• AFM allows imaging of surface topography with subnm resolution, and lateral resolution limited by radius of curvature of tip.
  • resolution ~ 1nm is possible with smaller, eg, carbon nanotube tips!
Electrostatic Scanning Force Microscopy (EFM)

Topographic AFM image
Magnetic Force Microscope (MFM)

MFM image of nanomagnets. Bright area (north pole) Dark area (south pole)

MFM image of recorded bits on thin-film disk recording media. The region imaged is 15x15 micrometers in dimension.
Scanning Gate Method

Charged AFM tip acts as a mobile gate. Changes in current measured simultaneously at each position.
Transmission electron microscope (TEM)

Comparison between a TEM and a slide projector.
(Bright field) imaging vs. electron diffraction

Obtaining the (a) projected image and (b) diffraction pattern of the sample
TEM examples
TEM examples


Single dopant study using z-contrast imaging. Ultrathin sample (5nm)
Scanning electron microscope (SEM)

Electrons are produced with an electron gun, similar to the one in a television.

The electrons are then accelerated through the Anode plate and focused with the Magnetic Lens.

The Scanning Coils force the electron beam to rapidly scan over an area of the specimen.

The specimen can be viewed in the Backscattered or Secondary mode, on a monitor.
SEM examples

Cat flea, X750
(Device) Fabrication

- Photo lithography
- E-beam lithography
- Nanoimprint lithography
- Self-assembly
- Direct growth of nanostructures in solution
- Direct growth of nanostructures with CVD

\{ \text{top-down} \}

\{ \text{bottom-up} \}
Photolithography

**Figure 3:** Lithography methods:
(a) contact,
(b) proximity and
(c) projection lithography.
e-beam lithography

LEO 440 SEM

microcomputer (with NPGS)
e-beam lithography

1) Expose

resist

Electron Beam

low sensitivity
high sensitivity
substrate

2) Development

Metal

3) Evaporation

4) Lift-off

electrodes

Smallest feature size ~20-50 nm, determined by backscattered electrons. Serial process.
Imprint lithography

Heating: $T > T_{\text{glass}}$

Alignment of mold and wafer

(140°-180°C)

Imprint: 40-130 bar

Imprint: 40 mbar-1 bar

Cool down

$T < T_{\text{glass}}$

UV-bake of resist

remove mold

Prof. Guo
EECS
Imprint lithography

Jim Heath group, Caltech
Self-assembly

Diblock copolymer

Two chemically distinct polymers mixed together.
stripe patterns result from repulsion between the two halves of each polymer molecule. Regular pattern developed after annealing since to obtain lower energy.
Self-assembly

\( f \): composition
Templated assembly of metal lines

Nature, 414, 735 (2001)
SiGe islands on Si

InGaAs islands on GaAs

growth: competition between strain energy and surface energy
Self Assembly of Metal Lines

- A giant number of nanostructures is formed in one simple deposition step.
- The synthesized nanostructures can reveal a high uniformity in size and composition.
- They may be covered epitaxially by host material without any crystal or interface defects.
Self assembly of nanostructures

ZL Wang group, Georgia Tech
Grow nanostructures in solution

Growth of semiconductor nanowires via catalyst mediated CVD

- Catalyst mediated CVD process
- Precisely controlled physical dimension (diameter/length)
- Perfect crystalline structure
- Broad range of chemical composition (group IV, III-V, II-VI)

Vapor-Liquid-Solid (VLS) growth process

\[ 	ext{AuSi (l)} \rightarrow \text{Au (s) + Si (s)} \]

\[ 	ext{SiH}_4 \rightarrow \text{Si} + 2\text{H}_2 \]
Growth of carbon nanotubes